Pollen-inferred regional vegetation patterns and demographic change in Southern Anatolia through the Holocene

Woodbridge, Jessie; Roberts, C. Neill; Palmisano, Alessio; Bevan, Andrew; Shennan, Stephen; Fyfe, Ralph; Eastwood, Warren J.; Izdebski, Adam; Çakirlar, Canan; Woldring, Henk

Published in:
Holocene

DOI:
10.1177/0959683619826635

The Holocene
2019, Vol. 29(5) 728–741

DOI: 10.1177/0959683619826635
journals.sagepub.com/home/hol
SAGE

Pollen-inferred regional vegetation patterns and demographic change in Southern Anatolia through the Holocene

Jessie Woodbridge,[1,2] C Neil Roberts,[1] Alessio Palmisano,[3] Andrew Bevan,[3] Stephen Shennan,[3] Ralph Fyfe,[1] Warren J Eastwood,[4] Adam Izdebski,[5,6] Canan Çakırlar,[7] Henk Woldring,[7] Nils Broothaerts,[8] David Kaniewski,[9] Martin Finné[10] and Inga Labuhn[11]

Abstract

Southern Anatolia is a highly significant area within the Mediterranean, particularly in terms of understanding how agriculture moved into Europe from neighbouring regions. This study uses pollen, palaeoclimate and archaeological evidence to investigate the relationships between demography and vegetation change, and to explore how the development of agriculture varied spatially. Data from 21 fossil pollen records have been transformed into forested, parkland and open vegetation types using cluster analysis. Patterns of change have been explored using non-metric multidimensional scaling (nMDS) and through analysis of indicator groups, such as an Anthropogenic Pollen Index, and Simpson's Diversity. Settlement data, which indicate population densities, and summed radiocarbon dates for archaeological sites have been used as a proxy for demographic change. The pollen and archaeological records confirm that farming can be detected earlier in Anatolia in comparison with many other parts of the Mediterranean. Dynamics of change in grazing indicators and the OJCV (*Olea, Juglans, Castanea* and *Vitis*) index for cultivated trees appear to match cycles of population expansion and decline. Vegetation and land use change is also influenced by other factors, such as climate change. Investigating the early impacts of anthropogenic activities (e.g. woodcutting, animal herding, the use of fire and agriculture) is key to understanding how societies have modified the environment since the mid–late Holocene, despite the capacity of ecological systems to absorb recurrent disturbances. The results of this study suggest that shifting human population dynamics played an important role in shaping land cover in central and southern Anatolia.

Keywords
Anatolia, archaeology, demography, land cover, pollen, vegetation

Received 1 June 2018; revised manuscript accepted 15 August 2018

Introduction

The vegetation history of Anatolia

Southern Anatolia can be broadly divided into three main subregions, namely, the coastal zone, the Taurus Mountains with intramontane lake basins and the inner Anatolian plateau (Iyigun et al., 2013). The modern landscape of Anatolia has developed over many millennia as a result of complex interactions between climate, human land use, natural and anthropogenic fire, and other factors, such as competition and species interactions. The landscape of inner Anatolia at the start of the Holocene was characterised by species-rich savannah-type grassland, which was replaced by *Quercus*-dominated parklands and wood pastures of lower diversity (Asouti and Kabukcu, 2014) into the mid-Holocene. In the wetter uplands of southwest Turkey, mixed conifer-deciduous forests replaced the *Artemisia*-chenopod steppe of the last glacial period (Van Zeist and Bottema, 1991).

Archaeobotanical and archaeozoological evidence demonstrates that plant and animal domestication developed earlier in Southwest Asia than in Europe, in particular within the Levant, showing that this was an important centre of agricultural origins

[1]School of Geography, Earth and Environmental Sciences, University of Plymouth, UK
[2]Department of Geography, College of Life and Environmental Sciences, University of Exeter, UK
[3]Institute of Archaeology, University College London, UK
[4]School of Geography, Earth and Environmental Sciences, University of Birmingham, UK
[5]Max Planck Institute for the Science of Human History, Germany
[6]Jagiellonian University, Poland
[7]Groningen Institute of Archaeology, University of Groningen, The Netherlands
[8]Department of Earth and Environmental Sciences, KU Leuven, Belgium
[9]EcoLab (Laboratoire d'Ecologie Fonctionnelle et Environnement), CNRS, Université Paul Sabatier-Toulouse 3, France
[10]Department of Archaeology and Ancient History, Uppsala University, Sweden
[11]Institute of Geography, University of Bremen, Germany

Corresponding author:
Jessie Woodbridge, School of Geography, Earth and Environmental Sciences, University of Plymouth, Drake Circus, Plymouth PL48AA, UK.
Email: Jessie.woodbridge@plymouth.ac.uk

(Colledge et al., 2004; Fuller et al., 2012). The first major human impact on ecosystem dynamics in southern Anatolia is not, however, detectable in pollen records until later in the Holocene (e.g. Eastwood et al., 1998). The so-called Beyşehir Occupation Phase (BOP; Bottema et al., 1986, 1990; Eastwood et al., 1998; Roberts, 2018; Van Zeist et al., 1975), which developed most extensively between ~3500 and 1300 cal. yr BP but with varied start dates detected between regions, is distinguished as a period of pronounced anthropogenic land-cover change. This phase began in the second and first millennia BC (~3000 ± 800 cal. yr BP) with declining forest cover and increasing pastureland, cereals and cultivated trees, such as olive and walnut (Eastwood et al., 1998; Roberts et al., 2018b). In southwest Turkey, Eastwood et al. (2007) identified that increased humidity coincided with pollen evidence for increasing human impact and intensification of agriculture during the BOP. Vegetation changes into the Hellenistic, Roman and early Byzantine periods (Table 1) reflected increasing evidence of human activity as documented in numerous studies. For example, Vermoere et al. (2002) identified periods of late-Holocene deforestation and cultivation within pollen records from Turkey, although this was accompanied by dissimilarities in the timing of agricultural phases. The BOP was followed by a period of land abandonment after AD 650 (1300 cal. yr BP) and reforestation, notably during the Arab–Byzantine wars of the 7th to 10th centuries AD (England et al., 2008; Izdebski, 2013; Roberts et al., 2018a, 2018b).

Cultural and demographic change in Anatolia

Human demographic change and associated land use has played a key role in shaping Holocene landscape alterations in central and southern Anatolia (Allcock, 2017; Allcock and Roberts, 2014; Roberts et al., 2018a, 2018b). There is evidence of a break in settlement in central Anatolia during the Younger Dryas (Baird et al., 2018), and as a consequence populations reacted more slowly to the improved climate that permitted the development of agricultural activity in the early Holocene in surrounding areas, such as the Levant (Roberts et al., 2018b; Palmisano et al., this volume). The Neolithic and related social changes during the early Holocene were associated with periods of population growth (Roberts et al., 2018b). In an assessment of long-term socio-environmental dynamics in central Turkey, Allcock (2017) identified human settlement changes that reflect the transformation of society from rural communities during the Neolithic to complex centralised polities, such as the Hittite, Persian and Roman Empires (Table 1), which builds upon a body of existing literature (e.g. Dalfes et al., 1997; Izdebski et al., 2016). She also highlighted how some periods of social change were associated with climatic or environmental instability, supporting earlier research (e.g. Kuzucuoğlu, 2015; McIntosh et al., 2000; Marro and Kuzucuoglu, 2007; Wilkinson, 1997).

The four major settlement cycles described by Allcock (2017) roughly correspond to the Neolithic, Bronze Age, Iron Age-Classical and Medieval-Modern periods. The most intense period of human occupation in Cappadocia occurred during Late Roman times (4th–7th centuries AD). Between Hellenistic and Late Roman times, the numerous cities of southern Anatolia were surrounded by agricultural land (Izdebski, 2013). However, a major demographic decline occurred between AD 650 and 900 in central and southwestern Anatolia associated with social and climatic changes. In the pollen record, this corresponded with a decline in the production of cereal and tree crops, and pastoral activity marking the end of the BOP (Roberts et al., 2018a). This was followed by regional differentiation in land use, such as agro-pastoralism in central Anatolia and cultivation of olives and other tree crops in western Anatolia.

Table 1. Archaeological periods in central and southwest Anatolia.

Age BP	BC/AD	Period
900–present	AD 1050–present	Medieval (Islamic) to modern
1600–900	AD 350–1050	Byzantine
2000–1600	50 BC–AD 350	Roman
2300–2000	350–50 BC	Hellenistic
3100–2300	1150–350 BC	Iron Age (including Persian)
3400–3100	1450–1150 BC	Late Bronze Age (Hittite Empire)
4000–3400	2050–1450 BC	Middle Bronze Age (including Old Hittite)
5000–4000	3050–2050 BC	Early Bronze Age
8000–5000	6050–3050 BC	Chalcolithic
10,300–8000	8350–6050 BC	Neolithic
>10,300	>8350 BC	Pre-Neolithic

Source: Allcock (2017).

Cultural change and climate

Climate trends in semi-arid regions, specifically variability in precipitation patterns, play an important role in socio-economic and cultural change, as water is a limited resource (Berger et al., 2016; Dean et al., 2015; Jones et al., 2006). The adoption of agriculture has been linked to the onset of the favourable early-Holocene climate, and subsequent periods of drought throughout the Holocene are reflected in archaeological records with evidence of social adaptations to reduced rainfall for crop production (e.g. Staubwasser and Weiss, 2006). A shift in climate seasonality was identified by Lewis et al. (2017), which could be linked to solar-forced climate change beginning ~8600 cal. yr BP. They describe changing water balance as an important factor influencing observed cultural changes at the Çatalhöyük archaeological site (located in south-central Turkey) in the late-Neolithic/early-Chalcolithic period and provide evidence for wet winter/early spring conditions during the early Holocene, reduced seasonality and possibly reduced local summer evaporation after 8300 cal. yr BP (Lewis et al., 2017; see also Roffet-Salque et al., 2018). Discontinuity in settlement patterns is often correlated with shortage of water, which would have left settlements vulnerable to any changes in climate (Lewis et al., 2017; Roberts et al., 2018a). The climate of southern Anatolia has altered significantly throughout the Holocene with many studies demonstrating periods of prolonged drought and significant shifts between wet and dry conditions (e.g. Dean et al., 2015; Woodbridge and Roberts, 2011). Three lake sediment oxygen isotope ($\delta^{18}O$) records derived from carbonates and diatoms (Nar Gölü only) provide an independent framework for Holocene hydroclimatic change, namely, Gölhisar in southwest Turkey (Eastwood et al., 2007) and Nar Gölü and Eski Acıgöl in central Anatolia (Dean et al., 2015; Roberts et al., 2001). Similarly to the trends described by Lewis et al. (2017), these records indicate a wetter early-Holocene climate.

This study examines vegetation dynamics and human population change across south-central and southwest Anatolia during the last 11 millennia, and addresses two key research questions: (1) What role have changing human populations and past climate trends played in shaping long-term land-cover change in southern Anatolia? and (2) what can be learnt about the impacts of past landscape management through understanding past demographic and vegetation change?

Methods

Pollen-inferred vegetation change

Fossil pollen datasets from 21 records across 14 sites within southern Anatolia have been analysed (Figure 1 and Table 2), and

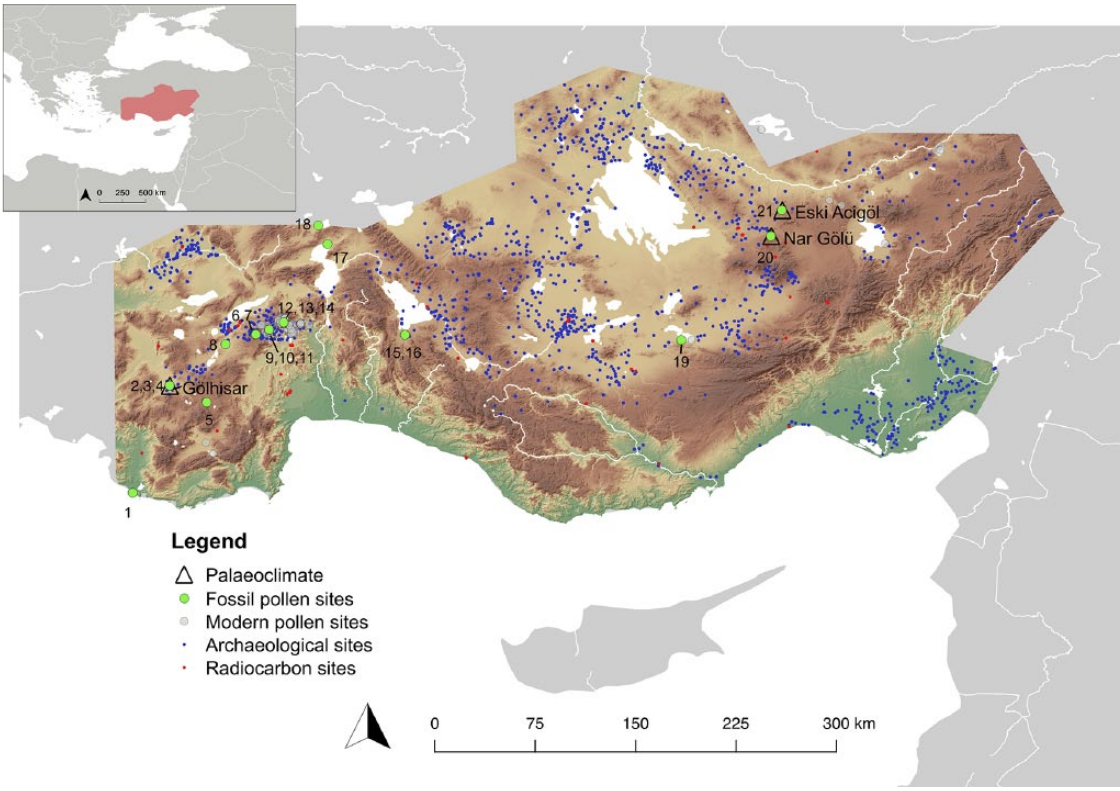

Figure 1. Locations of modern pollen (grey) and fossil pollen (green) sites, archaeological (blue) and radiocarbon sites (red) and palaeoclimate records (black triangles). The topographic map is shown for the region of south-central Anatolia analysed within this study. Site numbers are provided with the fossil sites (see Table 2 for further information).

different approaches employed to identify key patterns of vegetation change. Most of these records are from the intermontane 'lake district' of southwest Turkey, with three from central Anatolia and only one from the coastal zone. This spatial bias means that human landscape changes in the fertile coastal plains of Pamphylia (around modern Antalya) and Cilicia (around modern Adana) are not registered in regional pollen data. Pollen datasets principally derive from the European Pollen Database (EPD) supported by sediment core chronologies produced by Giesecke et al. (2014). Published pollen records also cover different time spans, with only a few sites spanning the whole Holocene. The limited number of early-Holocene pollen records means that regional syntheses of vegetation clusters may not be representative of the case study area's landscape ecology prior to 7000 cal. yr BP. Cluster analysis and community classification, which involved calculating the median and interquartile range of all pollen taxa within samples that fall into each cluster group (Perez et al., 2015), were used to identify major vegetation groups in Mediterranean-wide modern and fossil pollen datasets (Davis et al., 2013; Leydet et al., 2007–2017). This paper focuses on a subset of these sites from Anatolia for continuous 200-year time windows throughout the Holocene. The pollen-based methods employed are described in detail in Woodbridge et al. (2018) and Fyfe et al. (2018), which also involved most of the indices described here. Simpson's index and non-metric multidimensional scaling (nMDS) have been used to explore patterns of diversity change and major variation in the datasets along with the percentage of Arboreal Pollen (AP%). nMDS is an unconstrained ordination technique providing insights into high-dimensional datasets, and is explained in detail in Legendre and Legendre (1983) and McCune and Grace (2002). When applying nMDS, the number of axes is chosen before analysis, which avoids hidden axes of variation unlike other ordination techniques. In this study, a two-dimensional ordination was chosen and Bray–Curtis dissimilarity was used to calculate the distance matrix for ordination. Simpson's index has been calculated for each pollen sample using percentage data. This index takes both species richness and evenness into account and is often used to explore diversity change in pollen datasets (e.g. Morris et al., 2014; Woodbridge et al., 2018). An API (Anthropogenic Pollen Index: *Artemisia, Centaurea*, Cichorioideae, *Plantago*, cereals, *Urtica* and *Trifolium* type; Mercuri et al., 2013a), an indicator group for cultivated trees (OJC: *Olea, Juglans* and *Castanea*; Mercuri et al., 2013b) with the addition of *Vitis* (*Olea, Juglans, Castanea* and *Vitis* (OJCV)), and a group of pastoral land use indicators (Artemisia, Chenopodiaceae, *Plantago lanceolata* and *Plantago major/media*, Asteroideae, Cichorioideae, *Cirsium*-type, *Galium*-type, Ranunculaceae and *Potentilla*-type; adapted from Mazier et al., 2006) and grazing indicators (*Plantago lanceolata, Rumex acetosa*-type and *Sanguisorba*; Roberts et al., 2018a) were also calculated to explore changes in the pollen data in relation to human land use. Oleaceae undiff. was grouped with *Olea* within the OJCV index as this taxon is most likely to represent degraded *Olea* grains, and other taxa within the Oleaceae family are routinely differentiated (e.g. *Fraxinus, Phillyrea*). Although many of these indicator groups are based on published literature that describe the taxa as 'anthropogenic indicators', many of these taxa are not only associated with anthropogenic activity, such as Chenopodiaceae, Asteroideae and Cichorioideae, which indicate natural steppe vegetation. The pastoral indicator group was developed using pollen sites in France, so is less informative about landscape change in Anatolia, but has been included to aid comparisons between case study regions within a Mediterranean-wide synthesis (Roberts et al., this volume).

Archaeologically inferred demographic change

Archaeological data have been obtained for a total of 1426 sites and 3804 excavated or surveyed settlements (occupation periods; Figure 1) to construct records of past demographic change using established methods (Palmisano et al., 2017; for the general approach, Shennan et al., 2013; Timpson et al., 2014; as specifically implemented in Bevan and Crema, 2018: modelTest,

Table 2. Metadata for fossil pollen and palaeoclimate records from central Anatolia.

	Code	Site name	Latitude	Longitude	Elevation	Contributor	Site type	Proxy type	Start and end date	Time windows (n)	References
1	OVAGOLU	Ova Gölü	36.26667	29.3	20	EPD	Small marsh in drained lake	Pollen	7400–1000	30	European Pollen Database
2	GOLHISAR1	Gölhisar	37.13333	29.6	951	Eastwood	Lake	Pollen and climate	10,600–200	21	Eastwood et al. (1999)
3	GOLHISH	Gölhisar Gölü	37.13333	29.6	951	EPD	Lake	Pollen	8800–1200	11	European Pollen Database
4	GHC	Gölhisar Gölü	37.13333	29.6	951	Eastwood	Lake	Pollen	2600–1000	6	Eastwood et al. 1999
5	SOGUT	Sögüt Gölü	36.9975	29.89833	1400	EPD	Drained lake	Pollen	8400–0	20	Van Zeist et al. (1975)
6	BEREKET1	Bereket1	37.54518	30.29506	1410	Kaniewski	Marsh	Pollen	2200–0	11	Kaniewski et al. (2007b)
7	BEREKET2	Bereket2	37.54518	30.29512	1410	Izdebski	Marsh	Pollen	1400–1200	2	Bakker et al. (2012)
8	PINARBAS	Pınarbaşı	37.46667	30.05	970	EPD	Lake	Pollen	4600–800	11	European Pollen Database
9	GRAVGAZ	Gravgaz	37.58425	30.40358	1215	Izdebski	Marsh	Pollen	1800–0	9	Bakker et al. (2012)
10	GRAVGAZ96	Gravgaz96	37.58425	30.40358	1215	Broothaerts	Marsh	Pollen	3000–0	16	Vermoere et al. (2002)
11	GRAVGAZ99	Gravgaz99	37.58425	30.40358	1215	Broothaerts	Marsh	Pollen	2400–0	13	Bakker et al. (2013)
12	AGLASUN06	Aglasun06	37.64157	30.52029	1140	Broothaerts	Stream	Pollen	8600–200	22	Vermoere (2004)
13	AGLASUN12	Aglasun12	37.64058	30.5225	1140	Broothaerts	Stream	Pollen	7600–0	27	Vermoere (2004)
14	AGLASUN13	Aglasun13	37.64258	30.52009	1140	Broothaerts	Stream	Pollen	7800–0	32	Vermoere (2004)
15	BEYSEHIR	Beyşehir Gölü I	37.54167	31.5	1120	EPD	Lake	Pollen	7400–0	22	European Pollen Database
16	BEYSEHIR1	Beyşehir 77 II III	37.54167	31.5	1120	Woldring	Lake	Pollen	4600–1600	22	Bottema and Woldring (1984)
17	HOYRAN	Hoyran Gölü	38.275	30.875	920	EPD	Lake shore, marsh	Pollen	5800–0	14	European Pollen Database
18	KARAMIK	Kararmik Batakligi	38.425	30.8	1000	EPD	Marsh, partly open water	Pollen	9800–0	7	Van Zeist et al. (1975)
19	AKGOL	Akgöl Adabag	37.5	33.73333	999	EPD	Lake	Pollen	10,400–1800	8	Bottema (1987: 295–310) cited in Aurenche et al. (1987)
20	NAR	Nar Gölü	38.3403	34.45671	1363	Eastwood	Lake	Pollen and climate	1600–0	9	England et al. (2008); Roberts et al. (2016)
21	ESKI	Eski Acigol	38.55028	34.54472	1270	Woldring	Lake	Pollen and climate	10,800–200	44	Woldring and Bottema (2001–2002)

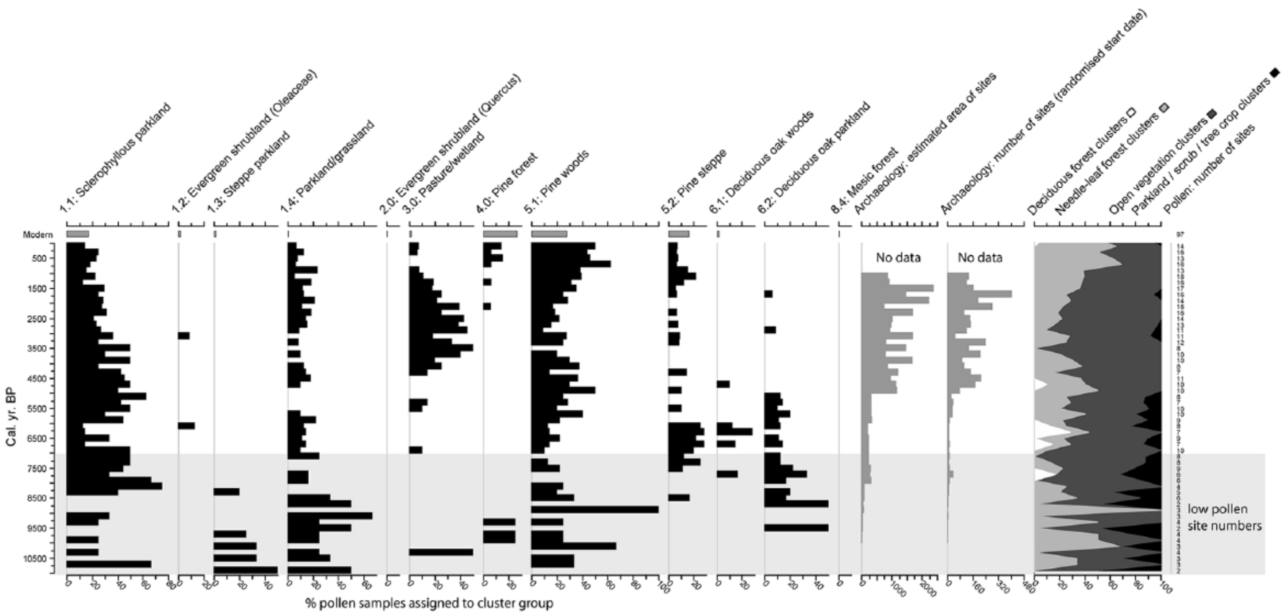

Figure 2. Pollen-inferred vegetation cluster groups presented as percentage of pollen samples (time windows) assigned to each vegetation cluster group for sites in south-central Anatolia and archaeological datasets (11,000 cal. yr BP–modern). The summary diagram shows amalgamated values of broad cluster groups, and the grey area highlights a period of low pollen site numbers.

'uncalsample'). Archaeological sites have been recorded, where possible, as georeferenced points per time slice (unprojected WGS84). For the purposes of this paper, we have chosen to deal exclusively with those places identified as human habitation sites or possible habitations, and hereafter we use the terms 'site' and 'settlement' interchangeably to refer to this subset. The settlement data cover the time period 9900 to 1100 cal. yr BP and summed radiocarbon dates extend from 11,000 to 6100 cal. yr BP, as there are insufficient data available covering times prior to or more recent than these periods. A spatial database of archaeological sites has been created through a comprehensive review, standardisation and synthesis of settlement data from reports and gazetteers relating to 52 archaeological surveys carried out throughout all three subregions of southern Anatolia, although there are some notable geographical gaps, such as the Pamphylian coastal plain (see Supplementary Information 3 (available online) for a complete list of references). Although the archaeological surveys carried out in Anatolia show a spatially variable intensity of investigation, most of them fall within the 'extensive' category (0.4–5 sites per kilometre square). Topographic variability is another issue to be considered in the Anatolian context as mountainous fringes and areas with rugged topography are marginal zones that have not commonly received as detailed archaeological attention as lowland areas for a series of practical reasons, such as difficult terrain and dense vegetation cover. Another issue is represented by the gap of the Middle Chalcolithic occupation in southwest Anatolia and the Burdur plain due to recognition and visibility problems related to either a poor knowledge of Middle Chalcolithic pottery assemblages or colluvium deposits covering floodplain sites (see Vandam, 2015). A major caveat is represented by the estimated size of settlements that in most cases indicate only the overall extent of mounds, but neither the size for a particular chronological phase nor the extent of any surrounding lower town. Therefore, the results derived from the analyses of the estimated settlement sizes have to be interpreted cautiously, as constituting evidence only about the patterns exhibited by relatively large, sedentary farming communities. The methods used in this paper to infer demographic trends from radiocarbon dates and archaeological settlement data build largely on previous works that seek to address issues such as 'wealth-bias' of particular site phases (Timpson et al., 2014), the artefacts in summed probability distribution (SPD) plots due to radiocarbon calibration curves (Weninger et al., 2015; Williams, 2012) and temporal uncertainty in archaeological site phases and periods (see Crema, 2012; Palmisano et al., 2017).

Within the analyses of the archaeological data, the 'site count' was calculated and the estimated 'site sizes' were summed for 200-year time steps in order to assess how population changes across time every 200 years. Bearing in mind that archaeological cultures result in larger or shorter time spans according to the dating precision of archaeological artefacts, we applied a probabilistic approach known as aoristic analysis to deal with the temporal uncertainty of occupation periods (Crema, 2012; Palmisano et al., 2017). In addition, to mitigate the discrepancy between wide chronological uncertainties and narrower likely site durations, we applied Monte Carlo methods to generate 'randomised start of occupation' periods for sites with low-resolution information (Crema, 2012; Palmisano et al., 2017). The resulting probabilistic distributions of site frequencies through time, based on the aoristic sums and Monte Carlo simulations, provide useful comparisons with the raw site frequency data and the summed settlement sizes. Consequently, the SPD of radiocarbon dates are binned into 200-year time slices to match the time windows used in the analysis of pollen sequences. We also calculated the median of the envelope of the randomised start date of sites, which is the result of a 1000-randomised start occupation date for sites, and binned this into 200-year time slices.

Palaeoclimate datasets

The palaeoclimate datasets (Figure 1 and Table 2) derive from lakes in central and southern Anatolia and provide records of $\delta^{18}O$ inferred hydroclimate (Nar Gölü: Dean et al., 2015; Eski Acıgöl: Roberts et al., 2001; Gölhisar Gölü: Eastwood et al., 2007). The records have been resampled to the same temporal resolution and converted to z-scores to allow inter-site comparisons and calculation of an average z-score for the region (see Finné et al., this volume, for further details).

Results

Vegetation, climate and demographic trends

The patterns of vegetation cluster group change (Figure 2) indicate an increase in sclerophyllous parkland (cluster 1.1) and pine steppe (cluster 5.2) after around 8000 cal. yr BP, which coincides with a decline in deciduous oak parkland (cluster 6.2). However, the limited number of pollen sites in the earlier Holocene makes interpretations more restricted for these vegetation cluster groups. One of the most striking trends in the pollen cluster group results is the increase and decline in pasture/wetland (cluster 3.0) between 4500 and 1300 cal. yr BP. This cluster is dominated by Cyperaceae pollen, and probably reflects a combination of increased upland grazing land, as indicated by the abundance of grass and grazing indicators in this cluster group, and local wetland sedge communities. In the last ~1800 years, there has been a significant expansion in pine woodland (cluster 5.1). The archaeological demographic proxy record indicates that population started increasing in the early Chalcolithic (~8000–7500 cal. yr BP) and grew substantially during the Bronze Age (~5000–3100 cal. yr BP), which was punctuated by cycles of 'boom and busts' throughout the Bronze Age (see Figure 3). A further increase in population then occurred in the Hellenistic and Roman periods (see Table 1 for a summary of Anatolian archaeological periods).

Pollen indicator groups offer a useful approach to explore key changes in vegetation community dynamics over time in line with cultural shifts. Figure 4 shows that arboreal pollen (AP%) has varied between 30% and 70% throughout the Holocene with a steady decline from 9000 to 2400 cal. yr BP and an increase after this time. There is a marked rise in cultivated trees between ~5000 and ~1500 cal. yr BP demonstrated in the OJCV index. The API indicates an increase in anthropogenic activity from 6500 cal. yr BP, while grazing pollen indicators steadily increased from 8500 cal. yr BP and declined in the most recent 1500 years. Simpson's index suggests that diversity increased in the early Holocene with consistent values throughout the records and a recent decline since 1500 cal. yr BP. Statistically significant relationships between the pollen and archaeological datasets (Tables 3 and 4) are demonstrated most clearly for the pasture/wetland vegetation cluster (3.0), which shows a strong positive relationship with the demographic proxies, and significant negative relationships between AP% and demographic change, indicating that larger populations were associated with increased pasture/wetland vegetation and a decline in the abundance of trees. A decrease in AP% could lead to decreased evaporation from vegetation and potentially higher run-off. Nevertheless, the Cyperaceae increase suggests lower lake levels, which could indicate drier climatic conditions or possibly human interference with catchment hydrology. There are also highly positive and significant relationships between the demographic proxies and the OJC/OJCV and API indices and grazing indicators, which reflect human land use. The nMDS axis scores summarise major variation in the pollen datasets and indicate periods of greater change around 6000 and 2000 cal. yr BP (Figure 4). The nMDS scores are significantly correlated ($p < 0.05$) with the demographic proxies (Tables 3 and 4), indicating that major change in the pollen data corresponds with demographic shifts.

When patterns within individual pollen records are examined in more detail, variability between sites is clearly identifiable. The results of two separate analyses are presented in Figure 5 (sites ordered from left to right reflecting SW to NE location): AP% (shown on the *x*-axis for each site), which indicates how open or closed the landscape is, and the cluster analysis derived 'vegetation clusters' are presented as symbols. Sites on the Anatolian plateau indicate greater abundance of grassland/parkland (1.4) throughout the Holocene (e.g. Eski Acıgöl), while those in the southwest Anatolian Lake District indicate that sclerophyllous parkland (1.1) or woodland dominated the landscape (e.g. Karamık, Beyşehir and Ağlasun). Similar vegetation shifts are shown between records,

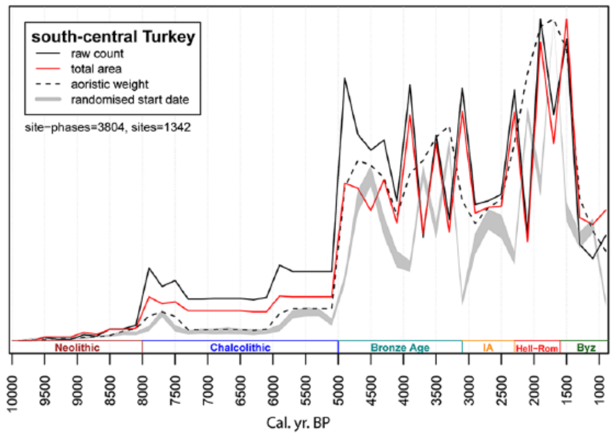

Figure 3. Normalised demographic trends for south-central Turkey based on settlement data (raw count, total area, aoristic weight and randomised start date) for the period 10,000 to 1000 cal. yr BP with key archaeological periods highlighted.

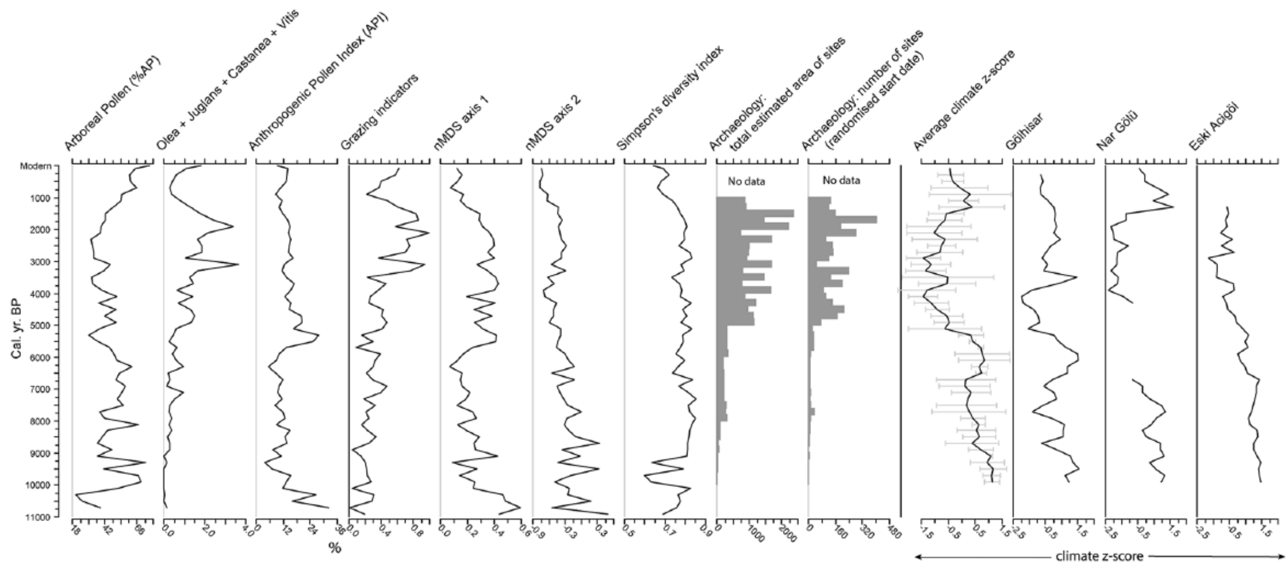

Figure 4. Pollen indicator groups: arboreal pollen (%AP); sum of *Olea, Juglans, Castanea* and *Vitis* (OJCV); Anthropogenic Pollen Index (API); summed grazing indicators; non-metric multidimensional scaling (nMDS) axis scores; and Simpson's diversity index averaged for all sites in the study area (11,000 cal. yr BP–modern). Archaeological demographic proxies from settlement data: total estimated area of sites and number of sites (randomised start date; 9900–1100 cal. yr BP). Normalised (z-scores) $\delta^{18}O$ hydroclimate (palaeoclimate) proxy records with average and standard deviation.

Table 3. Spearman's rho correlations between the pollen and archaeological datasets (upper value within each cell: *r* value and lower value: *p* value; significant *p* values: below 0.05 are shaded grey; 9900–1100 cal. yr BP).

	Raw count of sites	Total estimated area of sites	Aoristic sum of sites	Number of sites
1.1: Sclerophyllous parkland	0.255	0.263	0.223	0.164
	0.091	0.081	0.141	0.281
4.0: Pine forest	−0.304	−0.296	−0.208	−0.19
	0.042	0.048	0.17	0.212
5.1: Pine woods	0.303	0.276	0.272	0.23
	0.043	0.067	0.07	0.128
1.3: Steppe parkland	−0.3	−0.3	−0.292	−0.283
	0.045	0.045	0.052	0.059
1.2: Evergreen shrubland (Oleaceae)	0.095	0.065	−0.003	−0.077
	0.534	0.672	0.987	0.613
5.2: Pine steppe	−0.005	0.017	−0.052	−0.031
	0.973	0.91	0.732	0.839
3.0: Pasture/wetland	0.664	0.693	0.73	0.731
	0	0	0	0
6.1: Deciduous oak woods	−0.1	−0.135	−0.099	−0.069
	0.514	0.375	0.519	0.653
1.4: Parkland/grassland	−0.3	−0.288	−0.302	−0.224
	0.045	0.055	0.044	0.139
6.2: Deciduous oak parkland	−0.396	−0.4	−0.408	−0.396
	0.007	0.006	0.005	0.007
Arboreal Pollen	−0.408	−0.423	−0.455	−0.439
	0.005	0.004	0.002	0.003
Non-arboreal Pollen	0.443	0.451	0.5	0.478
	0.002	0.002	0	0.001
Oleaceae	0.783	0.784	0.791	0.807
	0	0	0	0
OJC	0.855	0.853	0.863	0.854
	0	0	0	0
OJCV	0.85	0.847	0.857	0.851
	0	0	0	0
API	0.478	0.454	0.474	0.461
	0.001	0.002	0.001	0.001
Grazing indicators	0.663	0.656	0.67	0.691
	0	0	0	0
Regional pastoral indicators	0.29	0.267	0.242	0.228
	0.054	0.076	0.109	0.133
Simpson's diversity index	−0.039	−0.039	−0.035	−0.025
	0.798	0.801	0.821	0.869
nMDS axis 1	0.473	0.48	0.511	0.49
	0.001	0.001	0	0.001
nMDS axis 2	−0.552	−0.553	−0.491	−0.46
	0	0	0.001	0.001

OJC: *Olea, Juglans* and *Castanea*; OJCV: *Olea, Juglans, Castanea* and *Vitis*; API: Anthropogenic Pollen Index; nMDS: non-metric multidimensional scaling.

such as pine woods (5.1) moving to pine steppe (5.2), and several records indicate an increase in pasture/wetland (3.0) from ~4000 cal. yr BP (e.g. Gölhisar, Ovagöl, Bereket and Pınarbaşı). Grass was abundant in the pollen records during the early Holocene; however, there is no clear relationship between grass abundance and the SPD of radiocarbon dates for this period (Figure 6). During the BOP, there was a clear increase in the OJCV index across most sites from 3500 to 1500 cal. yr BP, which is also reflected by peaks in the demographic proxies around these times (Figure 7). The increase in the OJCV index began earliest in the one pollen record available from the coastal zone (Ovagöl).

Within the palaeoclimate datasets (Figure 4) higher (more positive) *z*-scores indicate wetter climatic conditions, while lower (more negative) values relate to drier climate. The average *z*-scores across all three sites show wetter conditions in the early to mid-Holocene (until ~5000 cal. yr BP), followed by drier conditions until ~1500 cal. yr BP. Values then increase again indicating a shift to wetter climate during Medieval times and then decline signifying a more recent drying phase in the last ~600 years, corresponding to the 'Little Ice Age'. Spearman's rank correlations between the pollen, archaeological and palaeoclimate datasets indicate strong statistically significant negative relationships between all of

Table 4. Spearman's rho correlations between the pollen, archaeological and palaeoclimate z-score datasets (upper value within each cell: *r* value and lower value: *p* value; significant *p* values: below 0.05 are shaded grey; for corresponding time periods).

	Gölhisar	Nar Gölü	Eski Acıgöl	Average z-score
1.1: Sclerophyllous parkland	−0.16	−0.281	−0.138	−0.204
	0.272	0.083	0.39	0.154
4.0: Pine forest	0.073	0.281	0.341	0.28
	0.617	0.083	0.029	0.049
5.1: Pine woods	−0.279	0.018	−0.023	−0.093
	0.052	0.913	0.886	0.519
1.3: Steppe parkland	0.183	0.159	0.288	0.246
	0.209	0.332	0.068	0.086
1.2: Evergreen shrubland (Oleaceae)	0.128	−0.202	−0.141	0.017
	0.38	0.218	0.378	0.908
5.2: Pine steppe	−0.034	0.043	0.143	0.155
	0.817	0.797	0.374	0.283
3.0: Pasture/wetland	−0.183	−0.73	−0.779	−0.677
	0.209	0	0	0
6.1: Deciduous oak woods	0.005	0.13	0.163	0.176
	0.971	0.431	0.308	0.222
1.4: Parkland/grassland	0.25	0.319	0.343	0.396
	0.083	0.048	0.028	0.004
6.2: Deciduous oak parkland	0.146	0.267	0.452	0.39
	0.317	0.1	0.003	0.005
Arboreal Pollen	0.086	0.451	0.484	0.391
	0.559	0.004	0.001	0.005
Non-arboreal Pollen	−0.108	−0.481	−0.474	−0.403
	0.459	0.002	0.002	0.004
Oleaceae	−0.175	−0.737	−0.644	−0.571
	0.23	0	0	0
OJC	−0.301	−0.719	−0.752	−0.692
	0.036	0	0	0
OJCV	−0.3	−0.725	−0.752	−0.693
	0.036	0	0	0
API	−0.353	−0.528	−0.219	−0.355
	0.013	0.001	0.169	0.011
Grazing indicators	−0.306	−0.596	−0.604	−0.645
	0.033	0	0	0
Regional pastoral indicators	−0.332	−0.392	−0.01	−0.205
	0.02	0.014	0.952	0.154
Simpson's diversity index	−0.179	−0.122	0.036	−0.153
	0.218	0.46	0.824	0.288
nMDS axis 1	−0.091	−0.524	−0.53	−0.415
	0.536	0.001	0	0.003
nMDS axis 2	0.372	0.268	0.406	0.41
	0.009	0.099	0.008	0.003
Raw count of sites	−0.473	−0.754	−0.743	−0.778
	0.001	0	0	0
Total estimated area of sites	−0.46	−0.696	−0.756	−0.758
	0.001	0	0	0
Aoristic sum of sites	−0.415	−0.714	−0.798	−0.775
	0.005	0	0	0
Number of sites	−0.486	−0.662	−0.729	−0.7
	0.001	0	0	0

OJC: *Olea, Juglans* and *Castanea*; OJCV: *Olea, Juglans, Castanea* and *Vitis*; API: Anthropogenic Pollen Index; nMDS: non-metric multidimensional scaling.

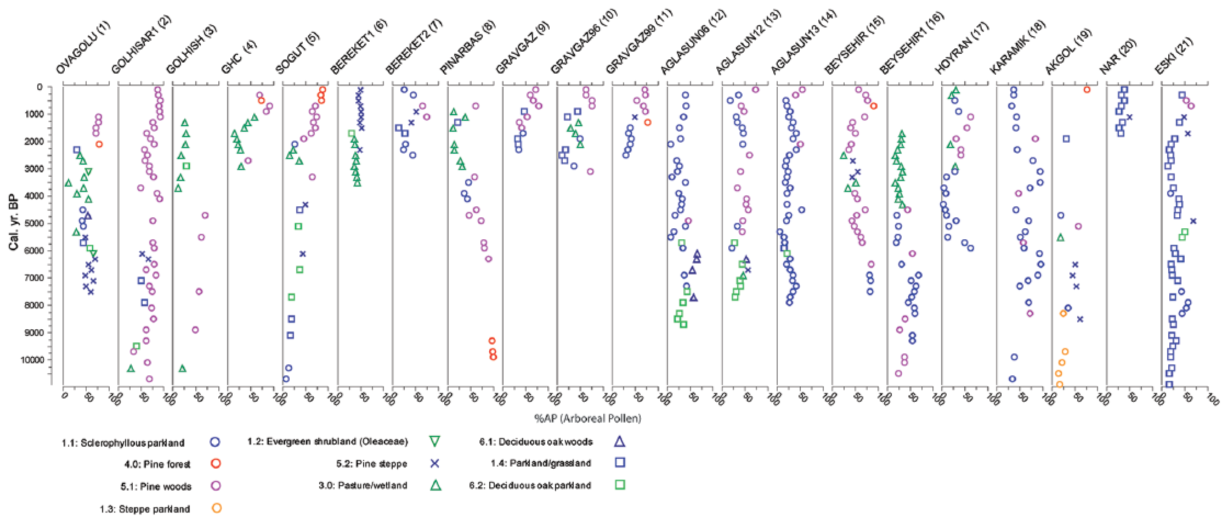

Figure 5. Sum of Arboreal Pollen (%AP) for each fossil pollen site plotted with vegetation cluster groups (symbols; 11,000 cal. yr BP–present). Sites 1 to 18 are located in southwest Anatolia and sites 19 to 22 are located on the Anatolian Plateau.

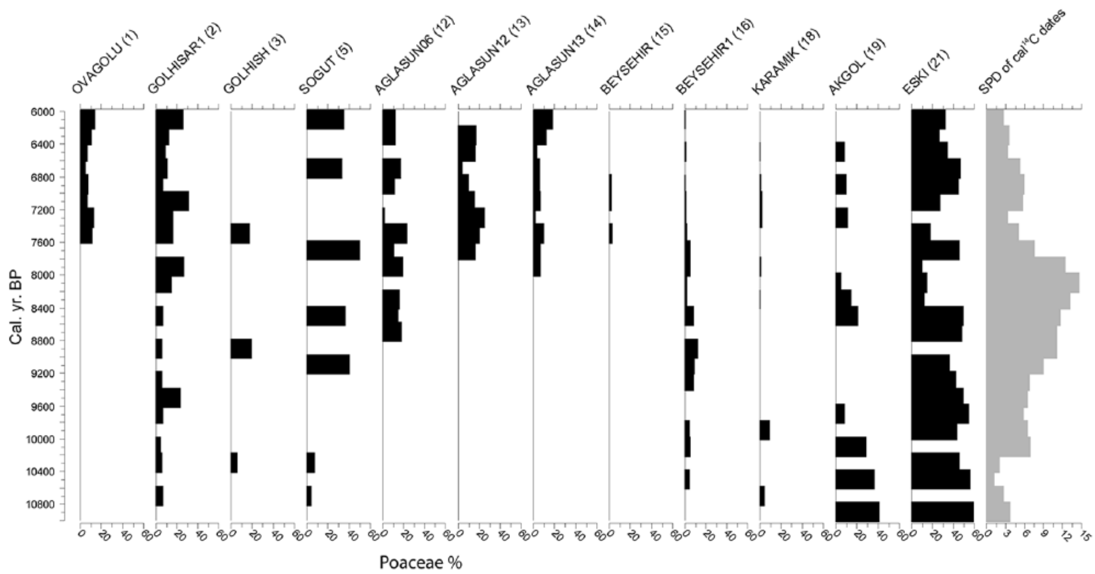

Figure 6. Poaceae (grass) % for pollen sites covering the early Holocene presented with summed probability distribution (SPD; 11,000–6000 cal. yr BP).

the climate records and the demographic proxies with r-values up to −0.78 (Table 3). The clearest significant relationships between the climate and pollen datasets are with the pasture/wetland cluster (3.0), which shows a negative relationship, indicating that pasture/wetland was more abundant when climate was drier. There are also significant relationships with a number of the pollen indicator groups, such as OJCV, API and grazing indicators, as shown for individual sites in Supplementary Information 2 (available online) which are all negatively correlated with climate (Table 3). Pollen nMDS scores are significantly correlated with the climate records, indicating that major patterns in the pollen datasets reflect climate trends.

Discussion

Demographic change, cultural transitions and landscape dynamics

Although efforts have been made to define a study region with good data coverage and congruence of datasets (pollen, archaeology and climate), the records from different data types may be clustered within some areas and not represented in others. Consequently, patterns are likely to be influenced by subregional dissimilarities in climatic, geographic, social and cultural history. The influence of these dissimilarities on the results and interpretations has been taken into account when interpreting patterns within and between the datasets, and sites are also shown individually in addition to the regional synthesis to illustrate site-level differences and characteristics (Figures 5–7). The results presented here have allowed a broad-scale comparison of long-term demographic and vegetation change, and they suggest that shifting human population dynamics played an important role in shaping land cover in central and southern Anatolia, as evidenced by the significant positive relationships between anthropogenic pollen indicator groups (API, OJCV and grazing indicators) and population increases (Figure 4 and Table 3). Abundance of vegetation cluster 1.4 (parkland/grassland) is evident during the early Holocene (Figure 3), which coincides with increased burning in the landscape of southern Anatolia, as demonstrated by Turner et al. (2010). The individual pollen records also indicate that grassland cover reached a maximum during the early Holocene, at least on the Anatolian plateau (Figure 6). This early grassland phase could have resulted from a combination of climate change and the influence of human land use, but most studies do not detect clear human impacts on vegetation until the later Holocene in Anatolia. Natural and anthropogenic use of fire, which is restricted by the availability of

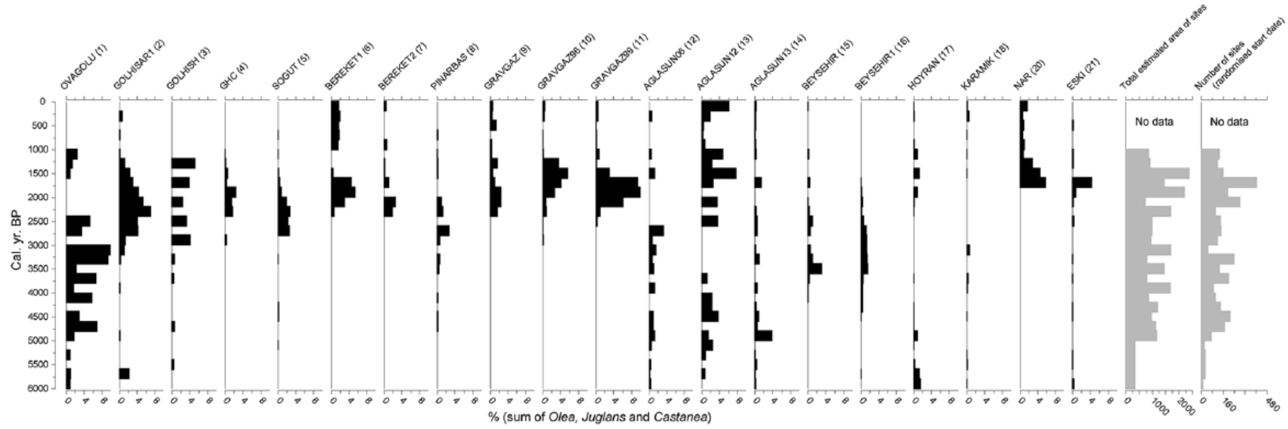

Figure 7. OJC (Olea, *Juglans* and *Castanea*) index for the period 6000 cal. yr BP to present for each pollen record presented with archaeological demographic proxies from settlement data: total estimated area of sites and number of sites (randomised duration; 6000–1100 cal. yr BP).

biomass for burning in drier sites on the Anatolian plateau, could have maintained grasslands, with climate appearing to act as a pacemaker for burning (Turner et al., 2008); however, these relationships require further investigation.

Archaeological trends for the early Holocene inferred from radiocarbon date densities (Roberts et al., 2018b) show a likely increase in population around 10,300 cal. yr BP continuing until ~7500 cal. yr BP (Figure 6). This corresponds to the Neolithic and early-Chalcolithic periods, when farming and sedentary village life were adopted in this region (Table 1). Previous studies also demonstrate evidence of abundant *Pistacia* in the early Holocene particularly in dry, high elevation areas, which is clearly demonstrated at Eski Acıgöl (Supplementary Information 1 (available online)), and also demonstrated in archaeological charcoal records of burned *Pistacia* wood (Asouti and Kabukcu, 2014). The trends identified by Allcock (2017) for Cappadocia match the wider regional population trajectories identified in the archaeological site survey data (Figure 3). The Early Bronze Age and Classical (Hellenistic–Roman–Early Byzantine) population peaks are clearly visible in the settlement density data shown in Figures 3 and 4.

The grassland phase was followed by the development of open oak parkland (~8500 cal. yr BP) that may have been managed by people (Figures 4 and 5). According to Asouti and Kabukcu (2014), these semi-arid oak woodlands, associated with increasing abundance of deciduous oak parkland (cluster 6.2), represent one of the earliest anthropogenic vegetation types in Southwest Asia as a consequence of prehistoric landscape practices and were not simply part of the 'natural' Anatolian vegetation. Therefore, this could imply that a pre-Neolithic baseline vegetation was absent in this region; by contrast, Holocene forest cover was much more extensively developed in the uplands of southwest Anatolia. However, the increase in oak parkland also reflects climatic changes and whether or not human populations would have been large enough to initiate detectable impacts on woodland cover at this time remains a matter of debate.

Throughout the Holocene, different vegetation types emerge (Figure 3), which can be interpreted in relation to changes in land use practices, such as increased sclerophyllous parkland (cluster 1.1) from 8400 cal. yr BP. Evidence of early farming activity has also been identified in pollen records from archaeological sites; for example, Eastwood et al. (2018) identified very high percentage of *Cerealia* pollen grains deposited over a short time period (~300 years) during the early Chalcolithic at Çatalhöyük in Anatolia. This early-Holocene phase was followed by dominance of clusters 1.1 (sclerophyllous parkland) and 6.2 (deciduous oak parkland) until 4500 cal. yr BP, and was then followed by an increase in Cyperaceae (shown in cluster 3.0: pasture/wetland) and tree crops indicated by the OJCV index (Figure 4) from ~5000 cal. yr BP. Lakes became shallower and dried out during periods of climatic desiccation (Figure 4) leading to increased Cyperaceae marshland. Cyperaceae also increased due to upland grazing at this time. The increase in the OJCV index that occurred earliest in the one pollen record available from the coastal zone (Ovagöl) suggests that systematic cultivation of tree crops, such as olive, started in the Eu-Mediterranean zone and only later moved into the interior Oro-Mediterranean zone.

Demographic changes coincide with some, but not all, of the vegetation changes identified in the pollen records. The SPD of radiocarbon dates from archaeological sites only covers the early to mid-Holocene and indicates a steady increase in population between 10,400 and 7800 cal. yr BP, followed by declining population (Figure 6). Asouti (2017) highlighted a myriad of factors that contributed to land use strategies in Southwest Asia during the early Holocene including natural agencies, such as climatic seasonality, and human factors, such as the experiences, community behaviours and mobility of people. Human land use could be reflected by the increase in parkland/grassland (cluster 1.4) in central Anatolia during this time (Figure 3), although the delayed re-establishment of forests in the early Holocene in Turkey has also been attributed to climatic factors (Bottema et al., 1990; Djamali et al., 2010; Van Zeist and Bottema, 1991). The relationships between demographic trends, human land use behaviours and vegetation changes are not straightforward, and it is uncertain whether human impacts by pre-Neolithic and Neolithic communities were large enough to cause widespread changes in the natural vegetation. Although detectable at an individual site level, such settlements and populations may have been too sparse and low in number to affect the region-wide landscape and other factors will also have influenced landscape change, such as seasonality of precipitation (Djamali et al., 2010; Lewis et al., 2017).

Oak parkland was maintained in central Anatolia until about 5000 cal. yr BP (cluster 6.2), after which time it was largely replaced by pastureland and by tree and cereal crops (Roberts et al., 2018b). This is demonstrated by the grazing indicator curve and OJCV index, which provides a simple anthropogenic signal, but which can also be influenced by taxa not associated with human land use, such as wild olive (Figure 4). The API is more difficult to interpret, since the ruderal plant taxa that contribute to this index would have responded to natural (e.g. climatic) as well as human disturbance in this region. Both south-central and southwest Anatolia experienced the BOP of agrarian land use, which also involved arboricultural practice and which increased after around 5000 cal. yr BP before declining again at 1500 cal. yr BP, indicating that tree crop cultivation, although spatially variable, was most significant during this period.

Initial human impact on regional vegetation in the uplands of southwest Anatolia is detectable somewhat later than on the plateau, most notably in late Chalcolithic times. At Ağlasun, in particular, a decline in deciduous oak woodland and an increase in anthropogenic pollen taxa at around 6000 cal. yr BP (Figure 5) have been attributed by Bakker et al. (2012) to clearance by early farming communities. The BOP, most extensively developed between 3500 and 1300 cal. yr BP, represents the clearest example of human-induced land-cover change in southern Anatolia during the Holocene. This phase was followed by a period in many pollen records that indicates 'rewilding' of the landscape with an increase in pine trees. This is reflected in the vegetation summary diagram (Figure 3) showing an increase in pine woods and a decline in open/parkland vegetation. The pine forest and pine woods cluster groups are frequently represented in individual pollen sequences since the mid- and late Holocene (e.g. Gölhisar, Gravgaz and Sogut) in the southwest of the case study region and are also represented in intermontane sites (e.g. Beyşehir and Hoyran) towards the north-east of the case study area. Roberts et al. (2018a) concluded that in Cappadocia (central Anatolia), the post-disturbance trajectory also took the regional socioecological system to a new and different state, rather than returning to a previous one, in this region dominated by agro-pastoralism (England et al., 2008).

Many previous studies have focussed on shorter time periods (e.g. Izdebski et al., 2015), small-scale (i.e. site-specific) comparisons between pollen and archaeological records, and identified similar timing in evidence of human occupation and the presence of land use pollen indicators (England et al., 2008). Within the current study, there are distinct differences between the pollen sites in the southwest and those on the central Anatolian plateau. The southwest is more mountainous and forested, whereas the plateau is drier. During the late Holocene, a marked increase in AP% is evident, mainly in the last 1500 years, particularly involving pine woods/forests, which indicates reforestation of areas previously used for agricultural land use. This is also shown in the cluster results (4.0, 5.1 and 5.2; Figure 3). A decline in population coincides with times of turbulence caused by conflict on the eastern frontier of the Byzantine Empire when much of southern and central Anatolia was deliberately depopulated and militarised (England et al., 2008; Haldon, 2016; Izdebski, 2013).

Significant relationships have been identified between the climate records and the demographic trends (settlement proxy); however, these relationships are complex and reflect many natural and cultural factors. The negative relationship between pasture/wetland and climate implies that when climate is drier, lake levels are lower and more habitats are created that support wetland plants (e.g. Cyperaceae). The synthesised pollen datasets analysed in this study do not appear to show any clear changes during the 9.3 and 8.2 ka climatic events, although they can be recognised in proxy-climate records from sites such as Nar Gölü (Dean et al., 2015). The 4.2 and 3.2 ka climatic events (e.g. Kaniewski et al., 2008) have been linked to societal collapse with centennial-scale drought intervals identified in palaeoclimate records during these periods (e.g. Dean et al., 2015; Massa and Şahoğlu, 2015). Population dynamics drawn from archaeological data seem to corroborate this picture in addition to the strong negative correlations ($r = \sim -0.70$) between palaeoclimate and demographic proxies (Table 3). The fact that some pollen taxa reflect both anthropogenic and non-anthropogenic factors complicates the interpretation of the indicator groups. Flohr et al. (2016) predicted four different potential societal 'responses' to sudden climatic change: collapse/decline of societies, long-distance migration, adaptation and no impact. The significant relationships between the OJCV index, API and grazing indicators and the climate records indicate that people may have adapted to long-term climatic shifts, for example, through diversification of subsistence practices. Flohr et al. (2016) suggested that the lack of a large-scale, severe impact that can be detected on Southwest Asian societies can be explained by the existence of such adaptation strategies and/or by the resilience of early farming communities. In more recent historical periods (the last 2000 years), a number of studies demonstrated that the impact of climatic changes on societal and landscape transformations was relatively limited. Adverse changes in climate conditions did not coincide with major transformations in the landscape and society (Haldon et al., 2014; Izdebski, 2013; Izdebski et al., 2016). Rather, a major landscape change, marking the end of the BOP, which took place in southern Anatolia around the 7th-century AD has been linked to degradation of the Eastern Roman (early Byzantine) political and socio-economic system, which required adaptation of social practices across Anatolia and much of the eastern Mediterranean. Similar studies of the later historical periods reported a lack of clear connections between climatic instability and socio-economic factors as well as landscape change during the Medieval Climate Anomaly (Xoplaki et al., 2016). However, a severe multi-year drought that occurred in Anatolia in the 1590s (AD) led to a prolonged social crisis and expansion of steppe pastures (White, 2011). Several episodes of 'social crises' occurred through this and the following century as a consequence of a complex combination of social, environmental and cultural factors. The increase in cluster 3.0 (pasture/wetland) between 4500 and 1300 cal. yr BP is likely to have been due both to climatic desiccation (including the 4.2 and 3.2 ka dry events), and to population rise and the development of pastoralism during Bronze Age to Classical times.

Other factors may also have influenced vegetation patterns, such as geomorphological changes (Kuzucuoğlu et al., 2019) and the impacts of long-term human impact and extreme climatic conditions upon soil properties, and thus site conditions for vegetation growth (e.g. Van Loo et al., 2017, who identified that soil erosion was driven by anthropogenic activities rather than climate change in southwest Turkey). Soil exhaustion in the past may have caused changes in vegetation composition not directly related to human impacts or climate change. Furthermore, vegetation recovery following human impact or climate change may be delayed or even halted when specific 'tipping points' are crossed. This might be related to site-specific environmental conditions making some sites more resilient than others and resulting in new equilibrium vegetation composition. For example, Kaniewski et al. (2007a) stress how contemporary land cover shows strong legacy effects of past human impact.

Landscape management

Understanding past demographic and vegetation change may provide useful information about the impacts of landscape management. Asouti and Kabukcu (2014) highlight how information about the origin and evolution of the Anatolian semi-arid oak woodlands is potentially of importance for reconstructing the changing ecologies and geographical distributions of domesticated crop species. Land use strategies that encourage the establishment and spread of deciduous oaks include sheep herding, controlling competing arboreal vegetation and woodland management (Asouti and Kabukcu, 2014). These practices could have affected landscapes in the mid-Holocene when, as our regional pollen synthesis shows, deciduous oak parkland (cluster 6.2) was more abundant in the landscape; this vegetation type is still extant in Cappadocia at present. In central Anatolia, this parkland ecosystem also includes economically important tree taxa, such as almond and wild fruit trees that are poorly represented in pollen diagrams (Woldring and Cappers, 2001). According to Gross (2012), poorly considered development projects are threatening biodiversity in Turkey and wildlife corridors provide opportunity to support conservation progress. Restoring biodiversity to its condition in, for example, earlier stages of the Holocene depends not only on reducing livestock grazing and wood-fuel cutting but also on incorporating these into a more sustainable system of socioecological management such as existed prior to the Iron Age.

Pollen records from Anatolia show clear evidence of environmental recovery following disturbance, most obviously in the post-BOP period. At Nar Gölü in Cappadocia, this included a significant re-expansion of oak woodland and decline in soil erosion after ~1300 cal. yr BP (England et al., 2008; Roberts et al., 2019, in press). In the uplands of southwest Anatolia, the re-wilding process favoured expansion of pine trees rather than the mixed conifer-broad leaf forests that had existed in the mid-Holocene (Figure 3; see Richardson, 2000, for a review of the ecology and biogeography of *Pinus*). The recent dominance of pine has probably been due to a combination of factors including soil loss during and after the BOP, along with continued grazing/browsing pressure from transhumant livestock herding, although open *Juniperus* woodland is also favoured by grazing. The relationships between population, land use and vegetation change are complex, and understanding regional trajectories of change can provide information about the characteristics of vegetation, resulting from different management practices and changing demographic pressures over time.

Conclusion

This study has highlighted the long-standing human transformation of vegetation in southern Anatolia. The early emergence of Neolithic agriculture meant that the oak parkland ecosystem of central Anatolia co-evolved as a consequence of natural and anthropogenic factors, including burning, grazing and woodcutting, and which may therefore have been maintained as a semi-natural agro-ecosystem. While changing human populations clearly influenced vegetation patterns, they did so in combination with other external controls, such as climate change. Hence, the increase in sedge pollen (cluster 3.0: pasture/wetland) between 4500 and 1300 cal. yr BP is likely to have been due both to climatic desiccation and the creation of upland pastureland during Bronze Age to Classical times. The precise timing of shifts in population and impacts on vegetation patterns do not show regular repetitive patterns over time. Pollen indicator groups such as cultivated trees (OJCV) and grazing indicators display significant positive relationships with demographic trends, especially during the BOP, and highlight how greater production of food would have been required for larger populations. Modern land management could benefit from improved understanding of the regional relationships between land use and vegetation change, and knowledge of how past land use practices promoted the resilience and potential for recovery of certain vegetation types, such as deciduous oak parkland.

Acknowledgements

Pollen data were extracted from the European Pollen Database (EPD; http://www.europeanpollendatabase.net/) and amalgamated from the work of data contributors. The EPD community is gratefully acknowledged, and gratitude is given to Michelle Leydet (the EPD manager) and many data contributors who have made a valuable contribution to this research. Thanks are also extended to Joan Estrany (University of the Balearic Islands) for his help organising a research workshop in Mallorca, and to Thomas Giesecke for making sediment core chronologies publicly available. This research is a contribution to the Past Global Changes (PAGES) project and its working group LandCover6k (coordinated by Marie-José Gaillard), which in turn received support from the Swiss Academy of Sciences.

Funding

This research has been funded by the Leverhulme Trust (Grant Number: RPG-2015-031).

Supplemental material

Supplemental material for this article is available online.

ORCID iDs

Alessio Palmisano] https://orcid.org/0000-0003-0758-5032
Andrew Bevan https://orcid.org/0000-0001-7967-3117
Ralph Fyfe https://orcid.org/0000-0002-5676-008X
Martin Finné https://orcid.org/0000-0001-7433-268X

References

Allcock SL (2017) Long-term socio-environmental dynamics and adaptive cycles in Cappadocia, Turkey during the Holocene. *Quaternary International* 446: 66–82.

Allcock SL and Roberts N (2014) Changes in regional settlement patterns in Cappadocia (central Turkey) since the Neolithic: A combined site survey perspective. *Anatolian Studies* 64: 33–57.

Asouti E (2017) Human palaeoecology in Southwest Asia during the early Pre-Pottery Neolithic (c. 9700–8500 cal BCE). In: Benz M, Gebel HGK and Watkins T (eds) *The Plant Story Studies in Early Near Eastern Production, Subsistence, and Environment: Neolithic Corporate Identities*. Berlin: Dörte Rokitta-Krumnow, pp. 21–53.

Asouti E and Kabukcu C (2014) Holocene semi-arid oak woodlands in the Irano-Anatolian region of Southwest Asia: Natural or anthropogenic? *Quaternary Science Reviews* 90: 158–182.

Aurenche O, Evin J, Hours F et al. (eds) (1987) *Chronologies in the Near East*. Oxford: BAR.

Baird D, Fairbairn A, Jenkins E et al. (2018) Agricultural origins on the Anatolian plateau. *Proceedings of the National Academy of Sciences* 115: E3077–E3086.

Bakker J, Paulissen E, Kaniewski D et al. (2012) Man, vegetation and climate during the Holocene in the territory of Sagalassos, Western Taurus Mountains, SW Turkey. *Vegetation History and Archaeobotany* 21: 249–266.

Bakker J, Paulissen E, Kaniewski D et al. (2013) Climate, people, fire and vegetation: New insights into vegetation dynamics in the Eastern Mediterranean since the 1st century AD. *Climate of the Past* 9: 57–87.

Berger J-F, Lespez L, Kuzucuoglu C et al. (2016) Interactions between climate change and human activities during the early to mid-Holocene in the eastern Mediterranean basin. *Climate of the Past* 12: 1847–1877.

Bevan A and Crema ER (2018) *rcarbon v1.1.2: Methods for calibrating and analysing radiocarbon dates*. Available at: https://CRAN.R-project.org/package=rcarbon (accessed 27 August 2018).

Bottema S and Woldring H (1984) Late Quaternary vegetation and climate of southwestern Turkey, part II. *Palaeohistoria* 26: 123–149.

Bottema S, Entjes-Nieborg G and Van Zeist W (eds) (1990) *Man's Role in the Shaping of the Eastern Mediterranean Landscape*. Rotterdam: A.A. Balkema.

Bottema S, Woldring H and Aytug B (1986) Palynological investigations on the relation between prehistoric man and vegetation in Turkey: The Beyşehir Occupation Phase. In: Demiriz H and Özhatay N (eds) *Proceedings of the 5th OPTIMA Congress, Istanbul 1986*, pp. 315–328.

Colledge S, Connolly J and Shennan S (2004) Archaeobotanical evidence for the spread of farming in the Eastern Mediterranean. *Current Anthropology* 45: 35–58.

Crema ER (2012) Modelling temporal uncertainty in archaeological analysis. *Journal of Archaeological Method and Theory* 19: 440–461.

Dalfes HN, Kukla G and Weiss H (1997) *Third Millennium BC Climate Change and Old World Collapse*. Berlin: Springer.

Davis BAS, Zanon M, Collins P et al. (2013) The European Modern Pollen Database (EMPD) project. *Vegetation History and Archaeobotany* 22: 521–530.

Dean JR, Jones MD, Leng MJ et al. (2015) Eastern Mediterranean hydroclimate over the late glacial and Holocene, reconstructed from the sediments of Nar lake, central Turkey, using stable isotopes and carbonate mineralogy. *Quaternary Science Reviews* 124: 162–174.

Djamali M, Akhani H, Andrieu-Ponel V et al. (2010) Indian Summer Monsoon variations could have affected the early Holocene woodland expansion in the Near East. *The Holocene* 20: 813–820.

Eastwood WJ, Fairbairn A, Stroud E et al. (2018) Comparing palynological and archaeobotanical data for early cereal agriculture at Chalcolithic Çatalhöyük, Turkey. *Quaternary Science Reviews* 202: 4–18.

Eastwood WJ, Leng MJ, Roberts N et al. (2007) Holocene climate change in the eastern Mediterranean region: A comparison of stable isotope and pollen data from Lake Gölhisar, southwest Turkey. *Journal of Quaternary Science* 22: 327–341.

Eastwood WJ, Roberts N and Lamb HF (1998) Palaeoecological and archaeological evidence for human occupance in southwest Turkey: The Beyşehir Occupation Phase. *Anatolian Studies* 48: 69–86.

Eastwood WJ, Roberts N, Lamb HF et al. (1999) Holocene environmental change in southwest Turkey: A palaeoecological record of lake and catchment-related changes. *Quaternary Science Reviews* 18: 671–695.

England A, Eastwood WJ, Roberts CN et al. (2008) Historical landscape change in Cappadocia (central Turkey): A palaeoecological investigation of annually-laminated sediments from Nar lake. *The Holocene* 18: 1229–1245.

Finné M, Woodbridge J, Labuhn I et al. (2019) Holocene hydroclimatic variability in the Mediterranean: A synthetic multiproxy reconstruction. *The Holocene* 29(5): 847–863.

Flohr P, Fleitmann D, Matthews R et al. (2016) Evidence of resilience to past climate change in Southwest Asia: Early farming communities and the 9.2 and 8.2 ka events. *Quaternary Science Reviews* 136: 23–39.

Fuller DQ, Willcox G and Allaby RG (2012) Early agricultural pathways: Moving outside the 'core area' hypothesis in Southwest Asia. *Journal of Experimental Botany* 63: 617–633.

Fyfe RM, Woodbridge J and Roberts N (2018) Trajectories of change in Mediterranean Holocene vegetation through classification of pollen data. *Vegetation History and Archaeobotany* 27: 351–364.

Giesecke T, Davis B, Brewer S et al. (2014) Towards mapping the late Quaternary vegetation change of Europe. *Vegetation History and Archaeobotany* 23(1): 75–86.

Gross M (2012) Turkey's biodiversity at the crossroads. *Current Biology* 22: 503–505.

Haldon J (2016) *The Empire That Would Not Die : The Paradox of Eastern Roman Survival, 640–740*. Cambridge, MA: Harvard University Press.

Haldon J, Roberts N, Izdebski A et al. (2014) The climate and environment of Byzantine Anatolia: Integrating science, history and archaeology. *Journal of Interdisciplinary History* 45: 113–161.

Iyigun C, Türkeş M, Batmaz I et al. (2013) Clustering current climate regions of Turkey by using a multivariate statistical method. *Theoretical and Applied Climatology* 114: 95–106.

Izdebski A (2013) *A Rural Economy in Transition: Asia Minor from Late Antiquity into the Early Middle Ages*. Warszawa: Fundacja im. Rafała Taubenschlaga.

Izdebski A, Koloch G and Słoczyński T (2015) Exploring Byzantine and Ottoman economic history with the use of palynological data: A quantitative approach. *Jahrbuch der Österreichischen Byzantinistik* 65: 67–110.

Izdebski A, Pickett J, Roberts N et al. (2016) The environmental, archaeological and historical evidence for regional climatic changes and their societal impacts in the Eastern Mediterranean in Late Antiquity. *Quaternary Science Reviews* 136: 189–208.

Jones MD, Roberts CN, Leng MJ et al. (2006) A high-resolution Late-Holocene lake isotope record from Turkey and links to North Atlantic and monsoon climate. *Geology* 34: 361–364.

Kaniewski D, De Laet V, Paulissen E et al. (2007a) Long-term effects of human impact on mountainous ecosystems, western Taurus Mountains, Turkey. *Journal of Biogeography* 34: 1975–1997.

Kaniewski D, Paulissen E, De Laet V et al. (2007b) A high-resolution late Holocene landscape ecological history inferred from an intramontane basin in the Western Taurus Mountains, Turkey. *Quaternary Science Reviews* 26: 2201–2218.

Kaniewski D, Paulissen E, van Campo E et al. (2008) Middle East coastal ecosystem response to middle-to-Late-Holocene abrupt climate changes. *Proceedings of the National Academy of Sciences* 105: 13941–13946.

Kuzucuoğlu C (2015) The rise and fall of the Hittite Empire in central Anatolia: How, when, where, did climate intervene? In: Beyer D, Henry O and Tibet A (eds) *La Cappadoce méridionale de la Préhistoire à la période byzantine*. Istanbul: Institut Français d'Etudes Anatoliennes, Ege Yay, pp. 17–41.

Kuzucuoğlu C, Kazancı N and Çiner A (eds) (2019) *Landscapes and Landforms of Turkey*. Berlin: Springer-Verlag.

Legendre L and Legendre P (1983) *Numerical Ecology*. Amsterdam: Elsevier.

Lewis JP, Leng MJ, Dean JR et al. (2017) Early Holocene palaeoseasonality inferred from the stable isotope composition of Unio shells from Çatalhöyük, Turkey. *Environmental Archaeology* 22: 79–95.

Leydet M (2007–2017) The European Pollen Database. Available at: http://www.europeanpollendatabase.net/ (accessed October 2017).

McCune B and Grace JB (2002) *Analysis of Ecological Communities*. Gleneden Beach, OR: MjM Software Design.

McIntosh RJ, Tainter JA and McIntosh SK (2000) *The Way the Wind Blows: Climate, History and Human Action*. New York: Columbia University Press.

Marro C and Kuzucuoglu C (2007) Northern Syria and upper Mesopotamia at the end of the third mill. BC: Did a crisis take place? In: Kuzucuoglu C and Marro C (eds) *The Crisis at the End of the 3rd mill. BC in the Middle Euphrates Valley: A Reality?* (Varia Anatolica, XIX). Paris: De Boccard; Istanbul: Ege Yay/IFEA, pp. 583–590.

Massa M and Şahoğlu V (2015) The 4.2 ka cal. yr. BP climatic event in West and Central Anatolia: Combining palaeo-climatic proxies and archaeological data. In: Meller H, Arz HW, Jung R and et al. (eds) *2200 BC – A Climatic Breakdown as a Cause for the Collapse of the Old World?* Halle (Saale): Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt, Landesmuseum für Vorgeschichte, pp. 61–78.

Mazier F, Galop D, Brun C et al. (2006) Modern pollen assemblages from grazed vegetation in the western Pyrenees, France: A numerical tool for more precise reconstruction of past cultural landscapes. *The Holocene* 16: 91–103.

Mercuri AM, Bandini Mazzanti M, Florenzano A et al. (2013a) Anthropogenic pollen indicators (API) from archaeological sites as local evidence of human-induced environments in the Italian Peninsula. *Annali di Botanica* 3: 143–153.

Mercuri AM, Bandini Mazzanti M, Florenzano A et al. (2013b) Olea, Juglans and Castanea: The OJC group as pollen evidence of the development of human-induced environments in the Italian peninsula. *Quaternary International* 303: 24–42.

Morris EK, Caruso T, Buscot F et al. (2014) Choosing and using diversity indices: Insights for ecological applications from the German Biodiversity Exploratories. *Ecology and Evolution* 4: 3514–3524.

Palmisano A, Bevan A and Shennan S (2017) Comparing archaeological proxies for long-term population patterns: An example from central Italy. *Journal of Archaeological Science* 87: 59–72.

Palmisano A, Woodbridge J, Roberts N et al. (2019) Holocene landscape dynamics and long-term population trends in the Levant. *The Holocene* 29(5): 708–727.

Perez M, Fyfe RM, Charman DJ et al. (2015) Later Holocene vegetation history of the Isles of Scilly, UK: Coastal influence and human land use in a small island context. *Journal of Quaternary Science* 30: 764–778.

Richardson D (2000) *Ecology and Biogeography of Pinus*. Cambridge: Cambridge University Press.

Roberts N (2018) Re-visiting the Beyşehir Occupation Phase: Land-cover change and the rural economy in the eastern Mediterranean during the first millennium AD. *Late Antique Archaeology* 11: 53–68.

Roberts N, Allcock SL, Arnaud F et al. (2016) A tale of two lakes: A multi-proxy comparison of Lateglacial and Holocene environmental change in Cappadocia, Turkey. *Journal of Quaternary Science* 31: 348–362.

Roberts N, Allcock SL, Barnett H et al. (2019) Cause-and-effect in Mediterranean erosion: The role of humans and climate upon Holocene sediment flux into a central Anatolian lake catchment. *Geomorphology* 331: 36–48.

Roberts N, Cassis M, Doonan O et al. (2018a) Not the end of the world? Post-classical decline and recovery in rural Anatolia. *Human Ecology* 46: 305–322.

Roberts N, Reed J, Leng MJ et al. (2001) The tempo of Holocene climatic change in the eastern Mediterranean region: New high-resolution crater-lake sediment data from central Turkey. *The Holocene* 11: 721–736.

Roberts N, Woodbridge J, Bevan A et al. (2018b) Human responses and non-responses to climatic variations during the last Glacial-Interglacial transition in the eastern Mediterranean. *Quaternary Science Reviews* 184: 47–67.

Roberts N, Woodbridge J, Palmisano A et al. (2019) Mediterranean landscape change during the Holocene: Synthesis, comparison and regional trends in population, land cover and climate. *The Holocene* 29(5): 923–937.

Roffet-Salque M, Marciniak A, Valdes PJ et al. (2018) Evidence for impact of the 8.2 kyr BP event on Near Eastern Neolithic farmers from multi-proxy records and climate modelling. *Proceedings of the National Academy of Sciences* 115(35): 8705–8709.

Shennan S, Downey SS, Timpson A et al. (2013) Regional population collapse followed initial agriculture booms in mid-Holocene Europe. *Nature Communications* 4: 2486.

Staubwasser M and Weiss H (2006) Holocene climate and cultural evolution in late prehistoric-early historic West Asia. *Quaternary Research* 66: 372–387.

Timpson A, Colledge S, Crema E et al. (2014) Reconstructing regional population fluctuations in the European Neolithic using radiocarbon dates: A new case-study using an improved method. *Journal of Archaeological Science* 52: 549–557.

Turner R, Roberts N and Jones MD (2008) Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. *Global and Planetary Change* 63: 317–324.

Turner R, Roberts N, Eastwood WJ et al. (2010) Fire, climate and the origins of agriculture: Micro-charcoal records of biomass burning during the last glacial–interglacial transition in Southwest Asia. *Journal of Quaternary Science* 25: 371–386.

Van Loo M, Dusar B, Verstraeten G et al. (2017) Human induced soil erosion and the implications on crop yield in a small mountainous Mediterranean catchment (SW-Turkey). *Catena* 149: 491–504.

Van Zeist W and Bottema S (1991) *Late Quaternary Vegetation of the Near East*. Rochester, MI: Reichert.

Van Zeist W, Woldring H and Stapert D (1975) Late Quaternary vegetation and climate of southwestern Turkey. *Palaeohistoria* 17: 55–143.

Vandam R (2015) The Burdur Plain Survey Project, SW Turkey. In search of the Middle Chalcolithic (5500–4200 BC). In: Steadman SR and McMahon G (eds) *The Archaeology of Anatolia: Recent Discoveries (2011–2014)*, vol. I. Cambridge: Cambridge Scholar Press, pp. 282–301.

Vermoere M (2004) *Holocene Vegetation History in the Territory of Sagalassos (Southwest Turkey): A Palynological Approach* (Studies in Eastern Mediterranean Archaeology (SEMA), vol. 6). Turnhout: Brepols.

Vermoere M, Bottema S, Vanhecke L et al. (2002) Palynological evidence for late-Holocene human occupation recorded in two wetlands in SW Turkey. *The Holocene* 12: 569–584.

Weninger B, Clare L, Jöris O et al. (2015) Quantum theory of radiocarbon calibration. *World Archaeology* 47: 543–566.

White S (2011) *The Climate of Rebellion in the Early Modern Ottoman Empire*. Cambridge: Cambridge University Press.

Wilkinson TJ (1997) Environmental fluctuations, agricultural production and collapse: A view from Bronze Age upper Mesopotamia. In: Dalfes HN, Kukla G and Weiss H (eds) *Third Millennium B.C. Climate Change and Old World Collapse, NATO ASI Series 149*. Berlin: Springer-Verlag, pp. 67–106.

Williams AN (2012) The use of summed radiocarbon probability distributions in archaeology: A review of methods. *Journal of Archaeological Science* 39: 578–589.

Woldring H and Bottema S (2001–2002) The vegetation history of East-Central Anatolia in relation to archaeology: The Eski Acıgöl pollen evidence compared with the Near Eastern environment. *Palaeohistoria* 43–44: 1–34.

Woldring H and Cappers RTJ (2001) The origin of the 'Wild Orchards' of Central Anatolia. *Turkish Journal of Botany* 25: 1–9.

Woodbridge J and Roberts N (2011) Late-Holocene climate of the Eastern Mediterranean inferred from diatom analysis of annually-laminated lake sediments. *Quaternary Science Reviews* 30: 3381–3392.

Woodbridge J, Roberts N, Fyfe R et al. (2018) Pan-Mediterranean Holocene vegetation and land-cover dynamics from synthesised pollen data. *Journal of Biogeography* 45: 2159–2174.

Xoplaki E, Fleitmann D, Luterbacher J et al. (2016) The Medieval Climate Anomaly and Byzantium: A review of the evidence on climatic fluctuations, economic performance and societal change. *Quaternary Science Reviews* 136: 229–252.